

# Dual Layer Corrugated Plate Antenna

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**Abstract**—A subwavelength slot fed high gain and compact dual layer corrugated plate antenna is presented in this paper. The antenna is realized by placing a second corrugated layer on top of the traditional corrugated plate antenna. The addition of the second layer generates waves reflection that produces multi-resonance frequencies to improve the antenna's bandwidth. Compared to a traditional single layer corrugated plate antenna, the proposed dual layer antenna has higher gain, lower side lobe level, narrower half power beam width (HPBW) and better impedance bandwidth. A prototype of the proposed antenna is built and tested. It has a measured peak gain of 16.3 dB at 11.3 GHz and an impedance bandwidth of 27%. The operating principle of the proposed antenna is also discussed and analysed.

**Index Terms**—corrugated plate antenna, high gain antenna, grooves, leaky wave, dual layer, subwavelength slot, electromagnetic wave reflection.

## I. INTRODUCTION

A subwavelength slot surrounded by symmetric and periodic corrugated structure has been widely investigated to deliver enhanced transmission in optical and microwave regions [1-4]. Inspired by the optical phenomenon and by scaling the structure dimensions up to microwave frequency range, highly directive microwave dual band corrugated antennas were realized in [5-7]. Further studies showed that using a slot array excited by multiple waveguides and surrounded by periodic corrugations could narrow the antenna beam width, and contribute to further enhancement in the antenna gain [8-9]. Moreover, a corrugated plate antenna with  $2 \times 2$  slot array with spacing larger than a wavelength and loaded with dielectric ribbons was proposed to suppress grating lobes and to increase the antenna gain [10]. In fact, the periodic grooves in those designs were used as a secondary radiation source that re-emits surface energy and modulates surface waves at the antenna surface [9-11]. Hence, dimensions and period of the grooves have strong effects on the antenna far-field performance due to the surface wave distribution on antenna surface [12]. To keep a low profile and to reduce metal thickness by adopting slot transversal resonant mode, a low profile single band and dielectric grooves loaded corrugated plate antenna was proposed in [13]. Other studies in [10] and [14] have shown that loading the antenna surface in the un-grooved region excites more surface waves and increases the antenna gain resulting in aperture efficiency enhancement.

Bandwidth limitation and large aperture size remain the main drawbacks of the traditional corrugated plate antennas that operate at microwave frequencies. In this paper, we propose a novel structure to reduce the antenna aperture size and to enhance both antenna gain and bandwidth by placing a second corrugated layer on top of the traditional

corrugated plate antenna. The proposed dual layer corrugated plate antenna has several advantages over a traditional single layer antenna. It has higher measured gain compared to similar size single layer antenna and higher impedance bandwidth than any similar antenna. In comparison with a traditional single layer corrugated antenna, measurement results show that the proposed dual layer antenna has 4.2 dB higher peak gain, 5.0 dB less side lobe level and 12.0% better impedance bandwidth.

## II. ANTENNA STRUCTURE

### A. Proposed Single Layer Corrugated Plate Antenna

A corrugated plate antenna is designed based on the design principles presented in [5-6] and [12]. The proposed antenna consists of a rectangular subwavelength slot in a middle of metallic slab surrounded by symmetrical and periodic corrugations as shown in Fig.1. On each side of the slot there are two symmetrical corrugations that boost the antenna gain and enhance the antenna far-field characteristics. The electromagnetic energy is coupled to the rectangular slot via a standard WR90 rectangular waveguide with UBR100 flange. The proposed antenna is modelled and simulated using CST Microwave Studio (CST MWS), where the antenna dimensions are optimized to enhance its gain at resonance frequency. The first estimation of the antenna parameters optimization routine is given by [6] and [12] as following:

$$\begin{aligned} SW &\ll \lambda \\ t &\approx n \frac{\lambda}{2} \\ p &\approx \lambda \\ k &\approx \frac{(2m+1)\lambda}{4} \end{aligned} \quad (1)$$

where  $\lambda$  is the operation free-space wavelength,  $SW$  is slot width,  $t$  is metal thickness,  $p$  is corrugations period,  $k$  is corrugations depth,  $m$  and  $n$  are integers. The antenna dimensions are optimized to boost the antenna gain at 10 GHz. The final dimensions for the antenna are:  $SW = 5.8 \text{ mm}$ , slot length  $SL = 15.5 \text{ mm}$ ,  $t = 6.5 \text{ mm}$ ,  $k = 4.5 \text{ mm}$ ,  $p = 25.4 \text{ mm}$ , corrugations depth  $d = 4.9 \text{ mm}$ , distance between 1st corrugations and slot  $r = 18.1 \text{ mm}$ , antenna length  $L = 135.0 \text{ mm}$ , antenna width  $W = 100.0 \text{ mm}$ . The antenna's prototype is shown in Fig.1 (c).

### B. Proposed Dual Layer Corrugated Plate Antenna

The configuration of the dual layer corrugated plate antenna is shown in Fig.2. The antenna consists of two corrugated plates on top of each other. The 1st layer is identical to the antenna that has been discussed in the previous section, while the 2nd layer is a corrugated plate with three identical slots in the centre of the structure. Introducing the 2nd layer dramatically enhances the antenna gain and bandwidth. The distance between both layers is  $h = 3.5 \text{ mm}$ , depth of 2nd layer corrugations is  $d1 = 4.7 \text{ mm}$ , and the width is  $k1 = 3.0 \text{ mm}$ , diameter of metal spacer posts is  $c = 8.0 \text{ mm}$ , 2nd layer slot width  $SW1 = 6.0 \text{ mm}$ , 2nd layer slot length  $SL1 = 17.0 \text{ mm}$ , distance between slots  $s = 1.5 \text{ mm}$ ,

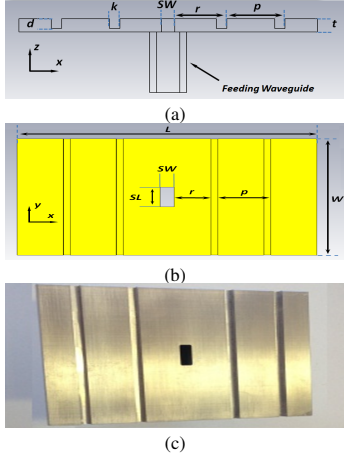


Fig. 1. Schematic of the single layer corrugated antenna; (a) cross section of side view, (b) top view and (c) photograph of the proposed antenna prototype.

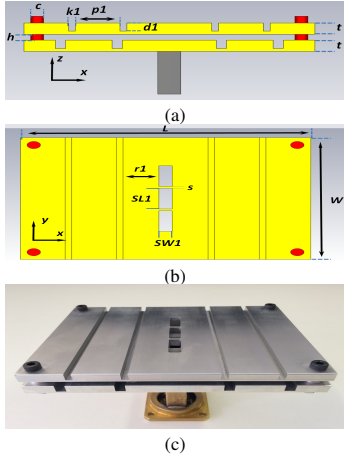


Fig. 2. Schematic of the dual layer corrugated antenna; (a) side view, (b) top view and (c) photographs of the proposed antenna prototype.

distance between 1st corrugation and slots  $r1 = 15.0 \text{ mm}$ , corrugation period  $p1 = 23.0 \text{ mm}$ ,  $W = 100.0 \text{ mm}$  and  $L = 130.0 \text{ mm}$ .

### III. RESULTS AND ANALYSIS

#### A. Single Layer Corrugated Plate Antenna

A prototype is built with the optimized dimensions. The reflection coefficient is measured using a network analyzer. A good agreement between simulated and measured reflection coefficient is found as shown in Fig.3. The antenna resonates at 10.0 GHz with a measured -10.0 dB bandwidth of 1.5 GHz. A small frequency shift of 50.0 MHz in the resonance frequency is observed between simulation and measurement which could be caused by fabrication tolerance and inaccuracy where the fabricated antenna has round slot corners due to milling procedure. The bandwidth of such a corrugated plate antenna is directly proportional to the slot width  $SW$ , while, resonance frequency at 10.0 GHz acting as transversal resonance is inversely proportional to the slot length  $SL$ . According to [6], the antenna's resonance frequency at 10.0 GHz is strictly controlled by  $SL$  dimensions, where  $SL$  dimensions determine

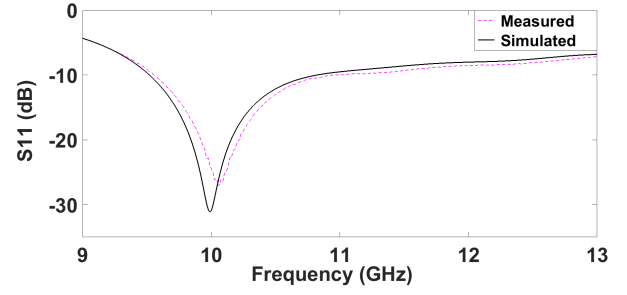


Fig. 3. Measured and simulated reflection coefficient of the single layer antenna.

the transversal slot resonance at

$$SL \approx \frac{\lambda_1}{2} \quad (2)$$

where  $\lambda_1$  is the wavelength of slot transversal resonance. In fact, the slot behaves as a rectangular waveguide antenna operating at the dominant  $TE_{10}$  mode which has a cut off frequency of  $f_c \approx \frac{c}{2SL}$ , hence equation (2) can be represented as

$$SL \approx \frac{\lambda_c}{2} \quad (3)$$

where  $\lambda_c$  is the cut off wavelength of the rectangular slot. The existence of the transversal resonance frequency at 10 GHz is approximately restricted for metal slab thickness  $t < (2/3)\lambda_c$ , where transversal resonance will vanish when the slab thickness is larger than  $(2/3)$  of the slot cut off wavelength  $\lambda_c$ . The thickness of metal does not affect the transversal resonance at 10.0 GHz when  $t < (2/3)\lambda_c$ , however, it has been reported in [5] and [6] thicker metallic slab is able to produce extra resonance frequency that depends exclusively on metal thickness  $t$ , hence a dual band corrugated plate antenna with metal slab thickness of  $t = 12.0 \text{ mm}$  was proposed to operate on 13 GHz and 16.5 GHz in [5-6][12]. The 1st resonance at 13.0 GHz which is the transversal resonance is only controlled by the dimensions of the slot length, while the 2nd resonance at 16.5 GHz which is the longitudinal slot resonance (Fabry-Perot like resonance) is controlled by the metal thickness  $t$  [5-6][12].

Our investigations confirm the finding that the longitudinal resonance frequency depends on the metal slab thickness; moreover, thicker metal supports unlimited number of resonance frequencies where the number of those resonance frequencies is directly proportional to the slot thickness, which is the same as the metal thickness  $t$ . Furthermore, the number of those longitudinal resonance frequencies depends solely on metal thickness, and can be approximated by:

$$t = \frac{43}{160} m \lambda_c \quad (4)$$

where  $m$  is an integer representing the number of longitudinal resonance frequencies. Hence, for the proposed antenna in this paper, there is no longitudinal resonance frequency since the metal thickness is  $t = 6.5 \text{ mm}$  which is less than  $(43/160) \lambda_c$ . Besides, the 1st longitudinal resonance starts to appear at 16.3 GHz when  $t$  is greater than  $(43/160) \lambda_c$  which is 8.33 mm. All longitudinal resonances are only in the range of dominant operation mode of the rectangular slot which

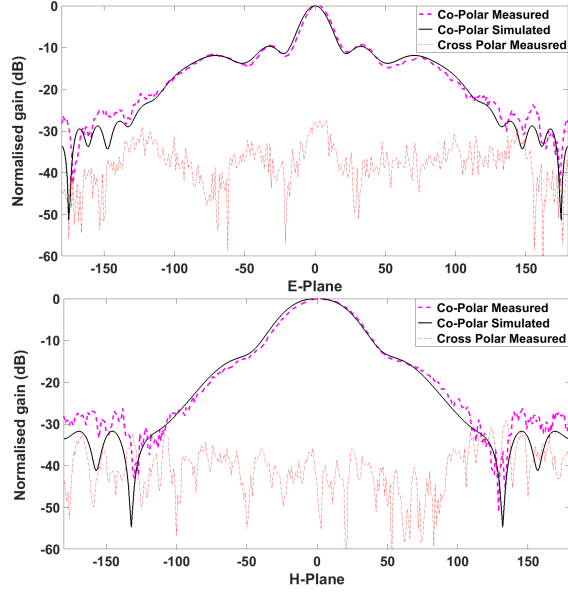


Fig. 4. Measured and simulated radiation patterns of the single layer antenna at 10.0 GHz.

is  $TE_{10}$  mode and there is no resonance beyond the cut off frequency of the next operating mode due to interference from multi-mode operations. For instance, in our design, the slot has dimensions of  $SL = 15.5 \text{ mm}$  and  $SW = 5.8 \text{ mm}$ , hence dominant mode operation is between 9.7 GHz and 19.4 GHz which is the cut off frequency of the  $TE_{20}$  mode. Finally, the only limitation to design a multi band antenna is the feeding waveguide single mode operation range, where the feeding waveguide should operate solely in the dominant  $TE_{10}$  mode in the antenna operation range.

The single layer antenna with two corrugations at each side of the slot has a maximum measured gain of 12.1 dB at 10.0 GHz while the simulated gain is 12.6 dB. The single layer antenna gain is measured using gain transfer method 'gain comparison method' described in [15] utilizing EMC 3115 double-ridged broadband standard horn antenna that have frequency range from 700.0 MHz to 18.0 GHz. Far-field radiation patterns in E-plane and H-planes are simulated and measured as shown in Fig.4, where good agreement between simulated and measured results is obtained. The measured half power beam width (HPBW) is  $18.0^\circ$  in the E-plane and  $45.0^\circ$  in the H-plane. The antenna has a very good cross polarisation level where it is more than 30.0 dB in both E and H planes over its entire bandwidth. The flat metal plate with dimensions of  $L \times W = 130.0 \text{ mm} \times 100.0 \text{ mm}$  has a gain of 6.2 dB with no corrugations. Reducing the flat plate dimensions to be the same dimensions as the aperture of the feeding waveguide reduces the metal slab gain from 6.2 dB to 5.7 dB only. This confirms the fact that the slot is working in similar manner to a waveguide antenna. Adding the two corrugations increases the antenna simulated gain to 12.6 dB at 10.0 GHz as shown in Fig.6. Adding extra periodic corrugations enhances the antenna gain till reaching a saturation limit [6]. The saturation number of corrugations for the single layer antenna shown in Fig.1 is five corrugations on each slot side with gain of

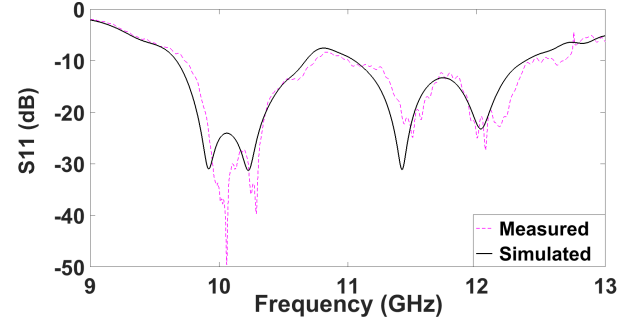


Fig. 5. Measured and simulated reflection coefficient of the dual layer antenna.

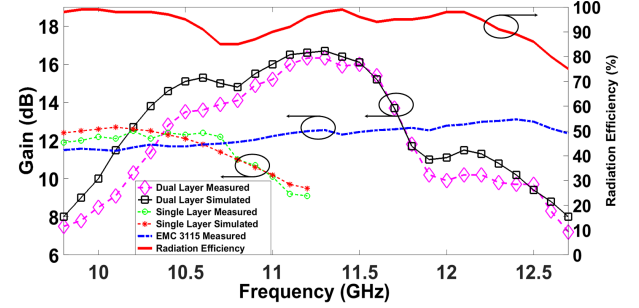


Fig. 6. Antennas gain and simulated radiation efficiency of the dual layer antenna.

14 dB (dimensions of the antenna with five corrugations is  $L \times W = 280.0 \text{ mm} \times 100.0 \text{ mm}$ ).

### B. Dual Layer Corrugated Plate Antenna

Introducing a 2nd layer to the traditional corrugated plate antenna on top of the 1st layer enhances the antenna bandwidth and gain. The measured -10.0 dB impedance bandwidth has increased by 1.2 GHz to be 2.7 GHz as shown in Fig.5. Moreover, adding two extra slots on the 2nd layer increases the antenna maximum measured gain by 4.2 dB as shown in Fig.6. The dual layer antenna has a measured peak gain of 16.3 dB at 11.3 GHz. The gain is measured using gain transfer method 'gain comparison method' described in [15]. The measured gain is 0.6 dB less than simulated one due to imperfect cable and fabrication. The 2nd layer corrugation depth, width, distance from slots and period are optimized to maximize antenna's gain at 11.3 GHz. At 11.3 GHz, the dual layer antenna has 4.0 dB less side lobe level compared to the single layer antenna in the E-plane and similar side lobe level (SLL) in the H-plane as shown in Fig.7. The antenna's HPBW in the H-plane is  $21.0^\circ$  with side lobe level of -15.0 dB, while the HPBW in the E-plane is  $15.5^\circ$  with SLL of -22.0 dB as shown in Fig.7. Moreover, the dual layer antenna has very low cross polarisation level of more than 25.0 dB in the E-plane and more than 30.0 dB in the H-plane over its entire bandwidth. The dual layer antenna has high simulated radiation efficiency as shown in the in Fig.6. It is higher than 98% from 9.9 GHz to 10.4 GHz, drops to 85% at 10.8, rises to 98% at 11.3 GHz and drops to 94% at 11.6 GHz, rises to 98% at 12 GHz, then drops to 95% and 80% at 12.2 GHz and 12.6 GHz, respectively.

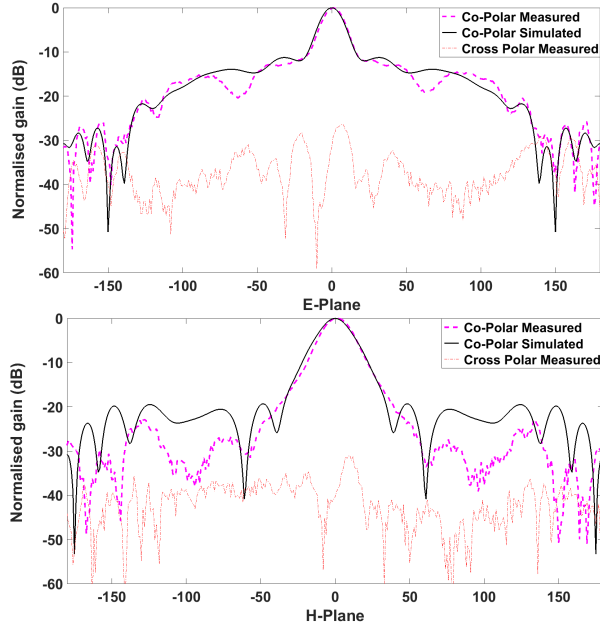


Fig. 7. Measured and simulated far-field radiation patterns of the dual Layer antenna at 11.3 GHz.

The proposed dual layer antenna dimensions and aperture efficiency are compared to a single layer antenna with two corrugations (grooves), a single layer antenna with five corrugations, an EMC 3115 double-ridged standard horn antenna and an X-band PE9856-15 smooth wall flared horn antenna as shown in Table I. The dual layer antenna has better aperture efficiency than single layer antennas and EMC 3115 horn, however, it has lower bandwidth, lower aperture efficiency and bigger aperture size compared to PE9856-15 horn antenna. The dual layer antenna is light, compact and has a low profile with a height of only 16.5 mm compared to 138.0 mm in case of PE9856-15. PE9856-15 is heavier and it is 8.4 times higher than the dual layer antenna, where the dual layer antenna height corresponds to  $0.6\lambda$  in comparison to  $5.2\lambda$  for the PE9856-15 horn. Finally, the dual layer antenna thickness can be minimized further without affecting its performance.

Bandwidth enhancement in the proposed dual layer antenna is due to multi-resonance frequencies caused by EM waves reflections between the two metal plates. Waves reflections cause constructive phase interference that creates extra resonance frequencies in which the total antenna bandwidth is increased. To gain more depth in the reflection mechanism between the two plates, three antennas are further investigated and simulated. The first antenna is when there is only a single slot on layer 2 and no corrugations on both layer 1 and layer 2 (labelled as Ant 1). The 2nd antenna is when there are two slots on layer 2 and there is no corrugations on layer 1 and layer 2 (labelled as Ant 2). The 3rd antenna is when there are three slots on layer 2 and there is no corrugations on layer 1 and layer 2 (labelled as Ant 3). The three antennas have identical dimensions to the dual layer antenna shown in Fig.2. It has been found that bandwidth enhancement of nearly 30% can be obtained in the three cases regardless the number of slots on the 2nd layer. Furthermore, in all three cases the

TABLE I  
ANTENNAS GAIN, SIZE AND APERTURE EFFICIENCY

Antenna	Gain (dB)	Dimensions (mm)	Aperture efficiency
Single Layer (5 grooves)	14 (Sim)	$280 \times 100 \times 6.5$	6.4%
Single Layer (2 grooves)	12.6(Sim);12.1(Meas)	$130 \times 100 \times 6.5$	10%; 8.9%
Dual Layer	16.9(Sim);16.3(Meas)	$130 \times 100 \times 16.5$	21%;18.5%
EMC 3115	12.3 (Meas)	$244 \times 159 \times 279$	2.5%
PE9856-15	15 (Meas)	$71.1 \times 52 \times 138$	48%

\*Aperture efficiencies are calculated at 10 GHz for single layer antennas and at 11.3 GHz for other antennas.

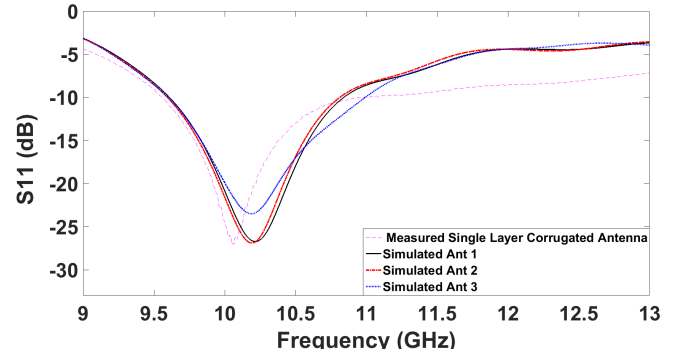


Fig. 8. Comparison of Ant 1, Ant 2 and Ant 3 reflection coefficient when  $h = 7.5 \text{ mm}$  and single layer antenna measured reflection coefficient.

number and position of extra resonance frequencies depend on the distance between both plates  $h$  which controls the phases of reflected waves. In the three cases (Ant 1, Ant 2 and Ant 3), there is a strong single resonance when the distance between both layers is  $h = \lambda/4 = 7.5 \text{ mm}$ , and the three antennas have similar  $S_{11}$  response to the single layer corrugated antenna performance shown in Fig.3. Ant 1, Ant 2 and Ant 3 have only single resonance at 10.0 GHz and no extra resonance is present as shown in Fig.8. This is due to phase cancellation between forward and backward running EM waves. The two metal plates are made of aluminum which has high conductivity and very low surface impedance  $Z_s$ , so the EM wave reflection phase at the two aluminum plates can be safely assumed  $\pm 180^\circ$ . Thus when  $h = \lambda/4$  both the forward and backward running EM waves are in phase cancellation [15] (reflection phase is defined as the phase difference between the backward and forward running waves [16]). In this case, the elimination of the reflected energy is attributed to destructive interference of the EM wave reflected by the 2nd layer surface with the forward running wave (incident wave) [15]. Both forward and backward waves have cancelled each other at  $h = \lambda/4$  and the antenna nearly resonates at 10.0 GHz as if no 2nd layer on top of the 1st layer. Hence, constructive phase interference can be exploited to design wide band antenna when  $h$  is optimized.



Furthermore, for the single layer corrugated plate antenna shown in Fig.1, the source of EM energy is the feeding waveguide as it couples energy to plate surface via the slot, where part of the coupled energy is radiated via the slot resulting in 6.2 dB gain and the rest of this energy is converted/transformed to unexcited/un-radiated surface waves that are polarized in the x-direction and propagate normal to metal plate surface and ultimately leaked at plate edges. The introduction of the corrugations excites these leaky surface waves resulting in antenna gain enhancement [6],[17-18]. Maximum surface waves excitation occurs when the sum of corrugations period and the corrugations depth equals to the operation wavelength where in phase re-transmission is achieved resulting in electric field radiation normal to metal surface. ( $p = 0.85 \lambda$  and  $p+d = 1.01\lambda$  at 10.0 GHz). Hence, the corrugations can be considered as secondary radiation sources where the radiation from those corrugations is super-positioned with the main radiation from the slot [9]. On the other hand, the radiation mechanism in the dual layer antenna is different. The EM energy is coupled from the 1st layer to the three slots in the 2nd layer. Those three slots become the primary radiation source as the E-field distribution shown in Fig.9. Hence, the dual layer antenna has a gain of 9.9 dB when there are no corrugations on the 2nd layer. The addition of the corrugation on the 2nd layer excites the un-radiated surface waves in a similar manner to the single layer antenna resulting in antenna gain increment of 7.0 dB, in comparison to 6.5 dB increment in the single layer case. The corrugation parameters on the 2nd layer are optimized to maximize the antenna gain at 11.3 GHz ( $p_1 = 0.86 \lambda$  and  $p_1+d_1 = 1.04\lambda$ ). The gain improvement in the dual layer antenna is due to coupling more power from the 1st layer to the three slots on the 2nd layer, hence the three slots are mainly responsible for the gain enhancement. The antenna gain is directly related to the number of slots on the 2nd layer as the antenna achieves a maximum gain of 13.0 dB with existence of one slot on the 2nd layer and 15.3 dB when there are two slots. Finally, the dual layer antenna with one slot/two slots on the 2nd layer can achieve similar bandwidth to the dual layer antenna with three slots. The existence of the corrugations on the 2nd layer is necessary to improve the overall antenna gain, however, the existence of the corrugations on the 1st layer has minor effect on the antenna gain. The dual layer antenna has achieved a maximum gain of 15.2 dB at 11.3 GHz when there are no corrugations on 1st layer, but the distance between both layers  $h$  and three slot dimensions on layer two need to be re-optimized to achieve this gain. Presence of the corrugations on the 1st layer contributes to 1.7 dB overall gain improvement. The presence of the corrugations on the 1st layer changes the electric field distribution in the cavity between both layers. When there are no corrugations on the 1st layer, the electric field is distributed uniformly in the cavity due to waves reflections between both plates and part of the EM energy is coupled to the three slots while the rest of the energy is lost/leaked at antenna edges. The corrugation on the 1st layer re-distribute the EM field so that high energy density is located beneath the three slots resulting in coupling more power to the three slots and less power leakage at the 1st layer

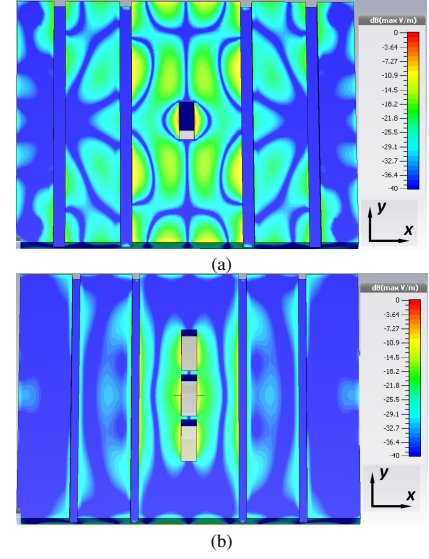


Fig. 9. Electric field distribution on the dual layer antenna normal to the metal surface at 11.3 GHz. (a) 1st layer and (b) 2nd layer.

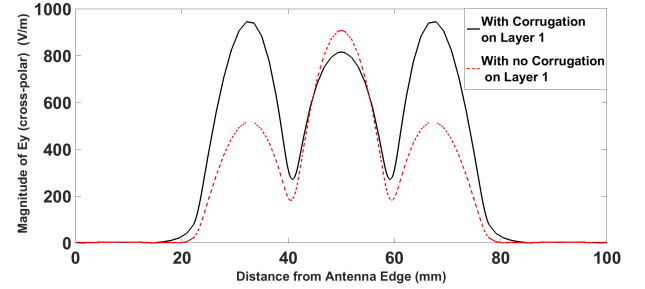


Fig. 10. Magnitude of cross-polar electric field on line parallel to y-axis at  $x = 0$  mm and 1 mm on top of the 2nd layer corrugated antenna.

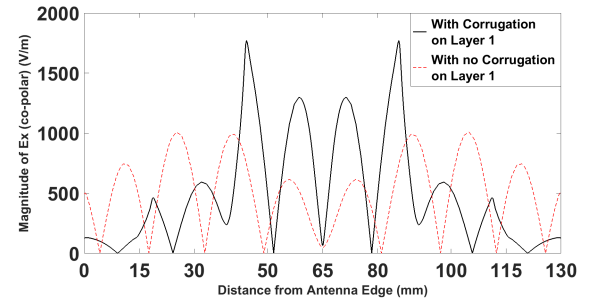


Fig. 11. Magnitude of co-polar electric field on line parallel to x-axis at  $y = 18.5$  mm and 1.0 mm on top of the 1st layer corrugated antenna.

edges as shown in Fig.10 and Fig.11.

Fig.10 shows the magnitude of the cross-polar electric field on a line parallel to y-axis and at  $x = 0$  and 1.0 mm on top of the 2nd layer corrugated antenna. Fig.10 reveals that more EM energy is coupled to the three slots when there are corrugations on the 1st layer. The dotted line in Fig.10 refers to the magnitude of cross-polar electric field on the line when there are no corrugations on the 1st layer, while the solid line refers to the magnitude of the cross-polar electric field on the line with the presence of corrugations on the 1st layer. There are three peaks of electric field and each of them is located at

the center of each slot. When there are no corrugations on the 1st layer, most of the electric energy is coupled to the slot in the center of the structure and less energy is coupled to the two other slots as the dotted curve shows. When the corrugations are present on the 1st layer, the electric field distribution is changed in the cavity and more energy is coupled to both slots resulting in boosting the antenna final gain. Furthermore, the co-polar electric field is observed at a line located at  $y = 18.5$  mm and parallel to x-axis as shown in Fig.11. The solid black line shows the co-polar electric field with the presence of corrugations on the 1st layer, while the dashed red line shows the field magnitude when there is no corrugations on the 1st layer. As shown in Fig.11, the magnitude of co-polar electric field in the area between the centre of 1st layer and the corrugations is much higher than the magnitude of the field when there are no corrugations on the same layer. Hence, the corrugations make the electric field concentrated in the area beneath the 2nd layer three slots allowing more EM energy to be coupled to the slots. Moreover, the presence of the corrugations on the 1st layer reduces the amount of EM energy lost at antenna edges through reducing EM wave reflection between both layers.

#### IV. CONCLUSION

This paper presented a design of novel dual layer corrugated plate antenna. Adding the 2nd layer on top of a traditional corrugated plate antenna reduced antenna size, enhanced antenna gain and improved impedance bandwidth. The measured prototypes have verified our designs and shown that the antenna peak gain has increased by 4.2 dB after adding the 2nd layer. The antenna achieved high impedance bandwidth with a measured peak gain of 16.3 dB.

Further analysis have shown that EM wave reflection between both layers created multi-resonance frequencies resulting in bandwidth enhancement, while EM energy coupling between the 1st layer and the three slots on the 2nd layer contributed to the gain improvement.

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